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Evaluation of Different Irrigation Methods for Improving Water Use Efficiency in Crop Production

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Abstract

Efficient irrigation management is essential for increasing crop productivity while conserving increasingly limited water resources. Conventional surface irrigation methods may result in substantial water losses through evaporation, runoff, and deep percolation. The present study was designed to evaluate the effects of different irrigation methods on crop growth, yield, irrigation water use, and water use efficiency. Four irrigation treatments were considered: conventional flood irrigation, furrow irrigation, sprinkler irrigation, and drip irrigation. The experiment was conducted using a randomized complete block design with three replications. Growth parameters, crop yield, irrigation water applied, and water use efficiency were evaluated. The illustrative results showed that drip irrigation required the lowest amount of irrigation water while producing the highest crop yield. Drip irrigation reduced irrigation water use by approximately 38% compared with conventional flood irrigation and increased water use efficiency substantially. Sprinkler irrigation also improved water use efficiency compared with flood irrigation, while furrow irrigation produced an intermediate response. The results demonstrate that improved irrigation methods can increase the productivity of irrigation water and contribute to sustainable agricultural production. Drip irrigation was the most efficient method under the conditions represented in this study, although the suitability of each irrigation system depends on crop type, soil characteristics, climate, field topography, water quality, installation cost, and management skill. The numerical results presented in this manuscript are illustrative and should be replaced with actual field observations before scientific publication.

Keyword: Irrigation, Water Use Efficiency, Drip Irrigation, Sprinkler Irrigation, Furrow Irrigation, Flood Irrigation, Crop Production, Water Conservation, Irrigation Management, Sustainable Agriculture

Introduction

Agriculture is the largest user of freshwater in many parts of the world, making efficient irrigation management essential for sustainable food production. Increasing population, climate variability, groundwater depletion, competition for water from other sectors, and changing rainfall patterns have increased the need to produce more agricultural output from every unit of available water.

Irrigation provides crops with water when rainfall is insufficient to meet crop water requirements. However, the efficiency of irrigation depends strongly on the irrigation method and its management. Water applied to a field does not necessarily become available to the crop. A proportion may be lost through surface runoff, evaporation, deep percolation, conveyance losses, or non-uniform application. Traditional flood or surface irrigation remains widely used because of its relatively low initial investment and simple operation. Nevertheless, conventional surface irrigation can result in relatively high water losses when fields are poorly leveled or irrigation is not properly scheduled.

Furrow irrigation can improve water application compared with uncontrolled flooding by directing water through channels between crop rows. However, considerable losses may still occur through deep percolation and evaporation, particularly when irrigation is poorly scheduled.

Sprinkler irrigation applies water through pressurized systems and distributes water over the crop or soil surface in the form of droplets. It can improve uniformity and reduce some field-level losses, although wind drift and evaporation may affect performance.

Drip irrigation delivers water directly or near the root zone through emitters. By applying small quantities of water at frequent intervals, drip systems can maintain relatively favorable soil moisture conditions while minimizing unnecessary wetting of the soil surface. This can improve water productivity, particularly for row crops and high-value crops.

Water use efficiency (WUE) is an important indicator for evaluating irrigation practices. At the crop-production level, WUE can be expressed as crop yield per unit of water consumed or, in practical field comparisons, as crop yield per

unit of irrigation water applied. The distinction is important because irrigation water applied is not necessarily equal to total crop evapotranspiration.

The Food and Agriculture Organization emphasizes that improved irrigation and water-management practices are important components of sustainable agricultural water management. Irrigation performance can be assessed using measures such as application efficiency, distribution uniformity, crop water use, and water productivity.

Improving irrigation efficiency does not simply mean applying less water. The objective is to apply water in the right amount, at the right time, and in the appropriate location so that crop water requirements are satisfied with minimum avoidable losses.

Therefore, evaluating different irrigation methods under comparable crop and soil conditions is important for identifying suitable strategies for improving agricultural water use efficiency.

Objectives

The objectives of the present study were:

1. To compare the effects of different irrigation methods on crop growth.
2. To evaluate the effect of irrigation method on crop yield.
3. To quantify irrigation water applied under different irrigation systems.
4. To determine water use efficiency under different irrigation methods.
5. To identify an irrigation method capable of improving water productivity.
6. To provide recommendations for efficient and sustainable irrigation management.

Materials and Methods

Experimental Site

The study was designed as a field experiment at an agricultural research farm. For an actual study, the precise location, latitude and longitude, climatic conditions, soil type, annual rainfall, temperature, and previous cropping history should be reported.

The experimental soil should be analyzed before the experiment for pH, electrical conductivity, organic carbon, available nitrogen, phosphorus, potassium, and soil texture. Because no original experimental dataset was supplied, the observations presented in this manuscript are illustrative.

Experimental Design

The experiment was designed using a randomized complete block design (RCBD) with four irrigation treatments and three replications.

The irrigation treatments were:

- T₁: Conventional flood irrigation
- T₂: Furrow irrigation
- T₃: Sprinkler irrigation
- T₄: Drip irrigation

All other agronomic practices, including variety, fertilizer application, weed management, and pest management, were maintained uniformly across treatments.

Crop Establishment

A suitable locally recommended crop variety was planted using recommended seed rate and row spacing. The exact crop and cultivar should be specified for an actual field experiment.

All plots were established under uniform soil and agronomic conditions.

Irrigation Treatments

Flood Irrigation

In the flood-irrigation treatment, water was distributed across the field surface using conventional surface irrigation. Irrigation was applied according to predetermined soil moisture or crop-growth criteria.

Furrow Irrigation

In furrow irrigation, water was supplied through channels formed between crop rows. This method reduces the area of direct soil wetting compared with uncontrolled flooding.

Sprinkler Irrigation

The sprinkler treatment used a pressurized irrigation system to distribute water over the crop area through sprinkler nozzles. Irrigation was scheduled according to crop water requirements and soil moisture.

Drip Irrigation

In the drip treatment, water was supplied through emitters located near the crop root zone. The system was operated according to crop water requirements and soil moisture conditions.

Measurement of Irrigation Water

The volume of irrigation water applied to each treatment was measured using a water meter or calibrated flow measurement device.

The total irrigation water applied during the crop season was calculated by summing the water applied during each irrigation event.

Measurement of Crop Growth

The following growth parameters were recorded:

- Plant height (cm)
- Number of leaves plant⁻¹
- Number of branches/tillers plant⁻¹, where applicable
- Leaf area
- Crop biomass
- Days to flowering
- Days to maturity

Measurements were taken at representative crop-growth stages.

Measurement of Yield

At physiological maturity, each plot was harvested separately. The harvested crop was weighed, processed, and converted to yield per hectare.

Depending on the crop, the following parameters were recorded:

- Number of productive plants or tillers m⁻²
- Fruit/pod/spike number
- Number of grains or seeds
- Thousand-seed weight
- Grain or marketable yield
- Straw/biomass yield
- Total biological yield

Water Use Efficiency

For comparison among irrigation treatments, irrigation water use efficiency was calculated as:

Irrigation Water Use Efficiency (IWUE) = Crop yield / Irrigation water applied

When yield is expressed as kg ha^{-1} and irrigation water as $\text{m}^3 \text{ha}^{-1}$, IWUE is expressed as:

kg m^{-3}

Crop water productivity can alternatively be calculated using crop evapotranspiration rather than irrigation water applied. This distinction should be clearly stated in an actual publication.

Water Saving

Water saving relative to conventional flood irrigation was calculated as:

Water saving (%) = $[(\text{Water applied under flood} - \text{Water applied under treatment}) / \text{Water applied under flood}] \times 100$

Statistical Analysis

The data should be analyzed using analysis of variance (ANOVA) appropriate for RCBD.

Treatment means should be compared using an appropriate multiple-comparison procedure at the 5% probability level.

For the present article, the values are illustrative and therefore should not be interpreted as statistically verified experimental observations.

Irrigation Water Applied

Table 2: Irrigation water applied under different irrigation methods

Irrigation method	Total irrigation water applied (mm)	Water applied ($\text{m}^3 \text{ha}^{-1}$)
T ₁ Flood	620	6200
T ₂ Furrow	540	5400
T ₃ Sprinkler	455	4550
T ₄ Drip	385	3850

The conventional flood-irrigation treatment required the greatest amount of irrigation water, whereas drip irrigation required the least.

Compared with flood irrigation, furrow irrigation reduced water application by approximately 12.9%, sprinkler irrigation by 26.6%, and drip irrigation by 37.9%.

Effect on Crop Yield

Table 3: Effect of irrigation method on crop yield

Irrigation method	Yield (t ha^{-1})	Increase over flood (%)
T ₁ Flood	4.18	—
T ₂ Furrow	4.36	4.3
T ₃ Sprinkler	4.62	10.5
T ₄ Drip	4.94	18.2

The highest crop yield was recorded under drip irrigation, followed by sprinkler, furrow, and flood irrigation.

The drip treatment produced approximately 18.2% greater yield than the flood treatment in the illustrative dataset.

Water Use Efficiency

Table 4: Water use efficiency under different irrigation methods

Irrigation method	Yield (kg ha^{-1})	Irrigation water ($\text{m}^3 \text{ha}^{-1}$)	IWUE (kg m^{-3})
T ₁ Flood	4180	6200	0.67
T ₂ Furrow	4360	5400	0.81
T ₃ Sprinkler	4620	4550	1.02
T ₄ Drip	4940	3850	1.28

Results

Effect of Irrigation Method on Crop Growth

Table 1: Illustrative effect of irrigation method on crop growth

Irrigation method	Plant height (cm)	Leaves/plant	Biomass (t ha^{-1})
T ₁ Flood	82.4	8.6	7.42
T ₂ Furrow	85.7	9.1	7.86
T ₃ Sprinkler	89.6	9.5	8.43
T ₄ Drip	94.8	10.2	9.16

The illustrative results showed that irrigation method affected crop growth. The lowest plant height and biomass were recorded under conventional flood irrigation, while the highest values were observed under drip irrigation.

The improved growth under drip irrigation may be associated with more uniform and frequent water supply near the crop root zone. Maintaining a favorable soil-moisture regime can reduce periods of water stress and improve nutrient uptake.

Sprinkler irrigation also produced greater growth than flood irrigation, while furrow irrigation produced an intermediate response.

The lower water requirement under drip irrigation was primarily associated with direct application of water to the crop root zone and reduced unnecessary wetting of the soil surface.

The yield improvement may be attributed to better soil-moisture management and reduced water stress during sensitive crop-growth stages.

Drip irrigation recorded the highest irrigation water use efficiency at 1.28 kg m^{-3} .

Sprinkler irrigation recorded 1.02 kg m^{-3} , while furrow irrigation recorded 0.81 kg m^{-3} . The lowest water use efficiency was observed under flood irrigation.

The results indicate that irrigation water productivity increased as irrigation application became more targeted and efficient.

Water Saving

Table 5: Water saving compared with conventional flood irrigation

Irrigation method	Water applied ($\text{m}^3 \text{ ha}^{-1}$)	Water saving (%)
Flood	6200	—
Furrow	5400	12.9
Sprinkler	4550	26.6
Drip	3850	37.9

Drip irrigation produced the greatest water saving, reducing irrigation water application by approximately 37.9% compared with conventional flood irrigation.

Discussion

Influence of Irrigation Method on Crop Growth

The illustrative results showed that irrigation method influenced plant growth. Crop growth was lowest under conventional flood irrigation and highest under drip irrigation.

The difference may be related to the distribution and timing of water application. In conventional flood irrigation, some portions of the field may receive excessive water while other areas may temporarily experience moisture stress. Excess water can also reduce soil aeration and increase losses through deep percolation.

Drip irrigation provides water close to the active root zone and can maintain soil moisture within a relatively favorable range. This may support continuous root activity and nutrient uptake.

Effect on Yield

The highest yield was observed under drip irrigation. Similar improvements are frequently associated with improved irrigation scheduling and more uniform water availability.

Yield is particularly sensitive to water stress during flowering, fruit or grain formation, and other critical growth stages. Efficient irrigation methods can help ensure that water is available during these periods.

Sprinkler irrigation also improved yield compared with flood irrigation, suggesting that more uniform water distribution can benefit crop development.

Water Consumption

The largest amount of irrigation water was applied under conventional flood irrigation. Surface irrigation may experience losses from evaporation, runoff, deep percolation, and conveyance.

Furrow irrigation reduced water use because water was confined primarily to furrows rather than distributed over the entire soil surface.

Sprinkler irrigation reduced water requirements further, although sprinkler systems may experience evaporation and wind-related losses depending on weather conditions.

Drip irrigation recorded the lowest water application in the illustrative experiment because water was applied directly to the crop root zone.

Water Use Efficiency

Water use efficiency provides a useful basis for comparing irrigation methods because it considers both crop output and water input.

The substantially greater IWUE observed under drip irrigation resulted from two combined effects:

1. Higher crop yield.
2. Lower irrigation water application.

Therefore, the benefit of drip irrigation was not simply reduced water consumption; it was the production of greater crop output from each unit of irrigation water.

Advantages of Drip Irrigation

The potential advantages of drip irrigation include:

- Reduced water losses.
- Direct root-zone water application.
- Better control over irrigation frequency.
- Reduced evaporation from non-cropped areas.
- Potential reduction in weed growth between rows.
- Compatibility with fertilization.
- Improved water productivity.
- Suitability for many row and horticultural crops.

However, drip irrigation also has disadvantages, including higher initial investment, emitter clogging, maintenance requirements, filtration needs, and the need for appropriate technical management.

Sprinkler Irrigation

Sprinkler irrigation can be useful where soil infiltration characteristics, field topography, or crop geometry make surface irrigation less efficient.

It can provide relatively uniform application when properly designed and operated. However, strong winds, high temperatures, and low humidity can increase evaporation and drift losses.

Sprinkler systems also require energy for pressurization, which should be included in economic and environmental assessments.

Furrow Irrigation

Furrow irrigation can be an effective intermediate technology because it generally requires lower capital investment than pressurized systems.

Its performance depends strongly on field slope, furrow length, infiltration rate, irrigation duration, soil type, and field leveling.

Improved furrow design and irrigation scheduling can substantially increase its efficiency compared with poorly managed flooding.

Conventional Flood Irrigation

Flood irrigation remains common because of its simplicity and low equipment requirement. However, poorly managed flood irrigation can result in significant water losses.

This does not mean that all surface irrigation systems are inefficient. Proper field leveling, appropriate irrigation depth, controlled inflow, suitable irrigation intervals, and good drainage can substantially improve surface-irrigation performance.

Thus, irrigation efficiency depends on both method and management.

Economic Considerations

The choice of irrigation method should not be based exclusively on water-saving potential.

Drip and sprinkler systems generally require greater initial investment than conventional surface irrigation. Farmers must therefore consider:

- Installation cost.
- Pumping and energy cost.
- Maintenance requirements.
- Availability of water.
- Crop value.
- Expected yield increase.
- System life.
- Labor requirements.
- Government incentives or subsidies where applicable.
- Cost of filtration and replacement components.

For high-value crops, the additional yield and water savings associated with drip irrigation may compensate for the higher installation cost. For low-value field crops, improved surface or furrow irrigation may sometimes provide a more economically attractive option.

A detailed cost-benefit analysis should therefore accompany an actual field experiment.

Environmental Implications

Efficient irrigation can contribute to environmental sustainability by reducing unnecessary water withdrawal and limiting deep percolation and runoff.

Reduced water application may also decrease the transport of soluble nutrients below the root zone. However, insufficient irrigation can reduce crop yield, so water conservation should not come at the expense of severe crop water stress.

Efficient irrigation should therefore be combined with:

- Soil-moisture monitoring.
- Weather-based irrigation scheduling.
- Proper fertilizer management.
- Drainage management.
- Prevention of salinity.
- Maintenance of soil organic matter.

The objective should be to maximize crop production per unit of water, rather than simply minimizing the volume of water applied.

Conclusion

The present study evaluated four irrigation methods—flood, furrow, sprinkler, and drip irrigation—with respect to crop growth, yield, irrigation water use, and water use efficiency.

The illustrative results showed that drip irrigation produced the highest crop yield and the greatest water use efficiency while requiring the lowest volume of irrigation water. Compared with conventional flood irrigation, drip irrigation reduced irrigation water application by approximately 37.9% and increased crop yield by approximately 18.2%.

Sprinkler irrigation also improved water productivity compared with flood irrigation, while furrow irrigation provided an intermediate improvement.

The results indicate that improved irrigation methods, particularly drip irrigation, can play an important role in increasing agricultural water productivity. Nevertheless, irrigation-system selection should consider crop type, soil texture, climate, topography, water availability, energy

requirements, investment cost, and farmer management capacity.

For sustainable crop production, irrigation efficiency should be combined with appropriate irrigation scheduling, soil-moisture monitoring, balanced fertilization, and good soil-management practices.

Recommendations

Based on the findings, the following recommendations are proposed:

1. Drip irrigation should be considered for crops where its technical and economic conditions are favorable.
2. Sprinkler irrigation can be adopted where uniform application and field conditions make it appropriate.
3. Furrow irrigation should be properly designed and managed to reduce water losses.
4. Conventional flood irrigation should be improved through proper field leveling and irrigation scheduling wherever replacement is not economically feasible.
5. Soil-moisture monitoring should be used to determine irrigation timing.
6. Irrigation should be scheduled according to crop growth stage and climatic demand.
7. Fertilizer application should be coordinated with irrigation through appropriate nutrient-management practices.
8. Economic analysis should be included when recommending irrigation technologies to farmers.
9. Long-term field experiments should be conducted under different soil and climatic conditions to validate water-saving performance.

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Conflict of Interest

The authors declare that there is no conflict of interest associated with this study.

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Data Availability

The numerical values presented in this manuscript are illustrative because no original experimental dataset was supplied. Actual experimental observations, irrigation records, crop-yield measurements, and replication-wise data should be used before submission to a scientific journal.

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